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3. Role of the computer in coronary care

The reduction of mortality in the coronary care unit which has resulted from rapid resuscitative measures and early recognition, prevention, and treatment of potentially dangerous arrhythmias is well documented. Though the majority of deaths in the coronary care unit are now due to the inability of the damaged myocardium to maintain functional circulation, there are still a significant number of deaths occurring because of inadequate early recognition and treatment of arrhythmias, inappropriate or too aggressive treatment with medication, failure to recognize early signs of pump failure and shock, or delay in using more aggressive forms of therapy.

It is, therefore, crucial, at this point in time, that our ability to determine and monitor the physiological parameters which most accurately reflect the status of the circulation be developed if further reduction in death rate and morbidity in the coronary care unit is to be expected. Only through close and frequent or continuous surveillance of such parameters as the intra-arterial pressure, peripheral resistance, cardiac output, stroke volume, central venous pressure, pulmonary artery pressure, oxygen saturation, etc., will it be possible to find the answers to such questions as:

1. What physiological measurements best predict or indicate onset of congestive heart failure or pump failure?
2. What are the causes of the various hemodynamic patterns which have been observed following myocardial infarction?
3. What combination of measurements and historical data give the best suggestion as to prognosis or course of therapy?
4. What are the effects of untreated arrhythmias on hemodynamics and prognosis?

The amount of data required to answer these questions will be so large and complex that electronic data processing will be essential. Therefore, the potential benefits from use of a computer in the coronary care unit are obvious. As a research tool it can be used to collect, store, and analyze vast quantities of physiological data. It can identify and retrieve pertinent data and can perform statistical manipulations on that data. It can also derive physiological parameters from direct and indirect measurements which would be difficult or impossible to derive by manual methods.

With the practical aspects of patient care, the computer can assist in several ways. Continuous monitoring of multiple variables on even one patient without a computer would pose an overwhelming task. With a catheter in a peripheral artery, pulmonary artery, or heart chamber, pressure measurements can be made frequently and automatically without bother to patient or nurse and the computer system can alert the nurse to significant changes when they occur. The response of the patient to vasopressors, Isuprel or fluid infusions can be monitored more closely and dangerous elevations of arterial pressure, venous pressure or heart rate prevented. With successful development of arrhythmia monitoring programs, the computer can relieve the nurse of responsibility for constantly watching an oscilloscope and alert the nurse to changes in rhythms when they occur. For the less experienced clinician or nurse, the computer can assist in making clinical judgements and suggesting therapy. Rapid review of the most pertinent bits of information from the patient's record can also be made more readily available to the physician or consultant on rounds in graphical or tabular form. These are only a few of the ways in which the computer is proving itself a useful tool for coronary care.

It would appear, however, that implementation of computer use and the value it will have in the coronary care unit will depend primarily on:

1. The ingenuity of those creating the computer-based monitoring system.
2. The degree of communication and understanding established among the bioengineer, computer programmer, and clinician.

For the computer to be used successfully in the coronary care unit, the clinician must be educated to its advantages and limitations as a tool for assisting him in the care of his patient. On the other hand, the engineer must understand the practical needs of the physician. Only in an environment where both can work side by side, can real problems be solved for improvement of patient care.

Since little had appeared in the literature as to how computers were being used in the coronary care units, a questionnaire was circulated in the spring of 1971 by the authors to the coronary care units of 15 hospitals throughout the U.S. who were known to either be using computers or engaged in clinical research on myocardial infarction. Only 6 responses were received. The following report is drawn from these questionnaires, reports in the literature, personal contact with coronary care investigators throughout the United States, and from the experience of the authors themselves.

HEMODYNAMICS

One of the ways in which the computer should be most useful in the coronary care unit is in the area of hemodynamic data collection. The laborious calculations which are part of any cardiac output determination or cardiac catheterization can be made very rapidly by the computer. Also, the automatic scheduling and taking of measurements, analysis, and storage of data, and generation of reports which go with on-line monitoring, all of which would be impossible to handle manually, are performed with ease by the computer.

A few institutions are already using the computer in a limited way to evaluate the hemodynamics of their myocardial infarct patients. These include: Duke University Medical Center, Durham, N. C.; the University of Alabama Medical School, Birmingham, Ala.; Massachusetts General Hospital, Boston, Mass.; Cedars Sinai Medical Center, Los Angeles, Calif.; and the Latter-Day Saints Hospital, Salt Lake City, Utah.

At other hospitals such as: Cornell Medical Center, Mayo Clinic, Stanford University, Cedars Sinai Medical Center, University of Rochester Medical School, plans are in progress to also use computers in the coronary care unit. Presently, to our knowledge, the Latter-Day Saints Hospital is the only coronary care unit monitoring hemodynamics on-line.

Investigators at Duke University are using the computer to assist them in performing a two-hour evaluation of all myocardial infarction patients on admission. This evaluation consists of cardiac catheterization and two-hours of hemodynamic monitoring. A computerized dye dilution method is used for determining cardiac output and a modification of the pressure pulse method is used for on-line monitoring during the two-hour period. The data collected are then analyzed by the computer using a regression equation which takes into consideration six measurements: stroke index, AV oxygen difference, blood pressure, heart rate, left ventricular pressure and right atrial pressure. From these measurements a prognostic index is calculated and decisions are made regarding subsequent therapy. The computer is, therefore, helping in a very practical way to determine which physiological parameters best correlate with morbidity and mortality and which are best for suggesting more aggressive forms of therapy (Wallace, personal communication).

At the University of Alabama in Birmingham, the computer is being used to make an assessment of left ventricular function from pulmonary artery pressure, left ventricular pressure, and cardiac output as measured by the dye dilution technique. The computer then lists the sequential outputs and pressures as well as the therapeutic maneuvers, such as medications and volume infusions. A ventricular function curve is constructed and interpreted for the clinician.

At Massachusetts General Hospital a Xerox Data Systems Sigma III Computer is being used to monitor heart rate, R-R intervals, and arterial pressure on one bed in an intensive study area. The computer also performs calculations for both thermal dilution and dye dilution cardiac output. Plans are being made to use the computer for monitoring more beds with more sophisticated programs (Russell, personal communication).

In Los Angeles, at the Cedars Sinai Medical Center, the thermal dilution method of determining cardiac output has been computerized on a PDP8 computer, and plans are in progress to use the computer for calculating left ventricular function on myocardial infarct patients from cardiac output, pulmonary capillary wedge, and left ventricular pressure measurements (Parmley, personal communication).

At the Latter-Day Saints Hospital, a Control Data 3300 computer monitoring system has been used to monitor more than 125 patients with acute myocardial infarction. In these patients, a teflon catheter is introduced into the subclavian artery through an 18 gauge thin-walled needle which has been placed percutaneously into the radial artery. The simple catheter system eliminates many of the difficulties usually associated with catheter introduction, since the catheter, needle, and insertion system are all contained

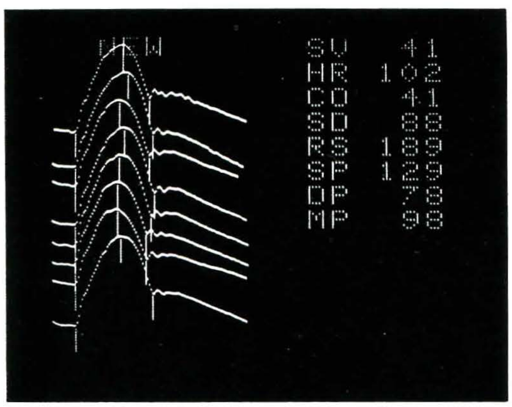

Fig. 1

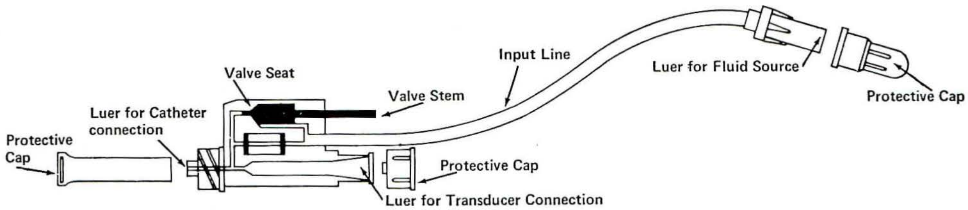

Fig. 2

within a sterile, disposable conduit. The catheter is connected to a small pressure transducer which is taped to the patient's arm. From the output of this transducer, a computer program detects the onset and end of systole of 16 consecutive beats and calculates stroke volume, heart rate, cardiac output, duration of systole, mean pressure, systolic pressure, and diastolic pressure (Fig. 1). The pressure pulse method of determining cardiac output is initially calibrated using an estimated cardiac output or a value previously determined by the dye curve method. The computer is scheduled to take measurements every 15 minutes, every two minutes, or on demand. The pressure pulse and ECG are displayed on a bedside oscilloscope as well as at the computer terminal oscilloscope on the nurse's desk. An immediate review of hemodynamic measurements is available at the computer terminal, and an eight-hour report and 24-hour printed summary can be obtained as a permanent record for the chart. Red warning lights are activated at the terminal in response to significant trends in heart rate, mean pressure, or stroke volume (Gardner *et al.*, 1970).

The performance of cardiac output measurements by dye dilution has been simplified considerably by the computer. Indocyanine green is injected through a central venous catheter while blood is sampled continuously from a brachial or femoral artery catheter. The arterial blood is withdrawn continuously through a Wood oximeter whose photocell output is transmitted directly through an analog to digital converter to the digital computer. At completion of sampling, cardiac output is calculated and displayed at the remote station, including a plot of the extrapolation over the original curve (Gardner *et al.*, 1970). Immediate access to data has not only improved the quality of data collected but has made collection of data during therapeutic manipulation much more simple.

From the experience to date with this system it is apparent that:

1. Inserting a small catheter into the subclavian artery via a needle in the radial artery is a safe procedure and causes little discomfort or inconvenience to the patient during several days of monitoring. Problems associated with clotting of the catheter have become insignificant with the development of a continuous flush system (Fig. 2).
2. Estimation of short-term changes in cardiac output and peripheral resistance can be accomplished from the central arterial wave form, but periodic calibration against an independent measurement, such as the dye method, is necessary if absolute values for cardiac outputs are to be inferred.
3. Use of the computer for on-line monitoring of arterial pressure and heart rate can be of considerable practical value in critically ill patients because these measurements can be taken automatically, more frequently, and more accurately than they could or would be taken by a nurse. Also, changes can be noted earlier and effects of medication can be titrated more accurately.
4. In our experience, the presence of an arterial line through which blood can be drawn encourages more frequent measurements of blood gases.

5. Although most clinicians like the additional hemodynamic information provided by this system, it is of value only if its accuracy can be insured, if it is readily available for easy review, and if obtaining it does not jeopardize the patient's welfare or result in a significant increase in cost.
6. Introduction of the computer into a coronary care unit has generated a more logical and deliberate approach to problem solving based on direct observation of the physiological disturbance when it occurs.

ARRHYTHMIA MONITORING

The rapid and accurate detection of arrhythmias in the coronary care unit is essential. To accomplish this, at the present time, a well-trained nurse must be taken out of circulation and posted in front of the monitor. In many units, because of shortage of nurses, this cannot and is not being done; therefore, monitor watching is often carried out in a haphazard fashion. Because the successful treatment of arrhythmias is directly related to the time lapse between recognition and treatment, a computer program which would provide continuous analysis of the ECG and an immediate alert of rhythm change should result in better patient care and fewer patient deaths. In addition, the ability of the computer to examine more ECG data, store, retrieve, correlate, and statistically manipulate it, makes the computer a most attractive research tool in the CCU.

Several investigators are examining digital computer methods for making on-line ECG monitoring practical, useful, and economically feasible. These computer systems vary in complexity from those which utilize pattern recognition logic to give specific rhythm diagnosis to those which only make measurements of the R-R intervals or look for premature ventricular contractions (PVCs).

G. Charles Oliver, Jerome Cox, and their associates at the Washington University School of Medicine in St. Louis, Mo., have programmed a computer to detect PVCs on-line. Their system, which is called the 'Arrhythmia Guard System', monitors two patients, detects and classifies beats as normal, abnormal, identifies PVCs, measures heart rate, and activates an alarm based on certain established sequences of PVCs. Evaluative studies have been carried out on this system and it has proven to be most helpful in the monitoring of patients with complicated arrhythmia problems. However, its economic feasibility and value in the routine monitoring of all myocardial infarction patients has yet to be demonstrated (Cox, personal communication; Oliver *et al.*, 1971).

Howard Hochberg, Cesar A. Caceres, and their associates at the U.S. Public Health Medical Systems Development Laboratory, Washington, D.C., have programmed a digital computer system to analyze the ECG on-line for rhythm and pattern. ECGs can be transmitted from the coronary care unit to the computer via a multi-channel analog data phone. This program is primarily oriented toward analysis of ECG morphology rather than rhythm and utilizes the 12-lead scaler clinical ECG. Computer program logic identifies the waves, measures a typical complex, and produces interpretable statements every 90 seconds. An evaluative study on this method is not yet available (Hochberg *et al.*, 1969).

At the Latter-Day Saints Hospital, Allen Pryor has developed, as part of a generalized ECG analysis system, a program which classifies arrhythmias from a single ECG lead. This program, which runs on a Control Data 3300 computer, is used in the coronary care unit to alert the nurse when a change in rhythm occurs in any patient. The ECG analysis is performed automatically either every 15 or every 2 minutes in sequence, following sampling of the arterial pulse for hemodynamic measurements. The rhythm diagnosis is compared with the diagnosis on the previous analysis, and if a significant change has occurred, a warning light is turned on at the computer terminal to alert the nurse. When she depresses the lighted button, the computer is interrupted and displays the prior and present rhythm diagnosis on the terminal display scope. Rhythm classification currently includes:

1. Sinus mechanism
2. Sinus arrhythmia
3. Regular rhythm – check P wave
4. Atrial fibrillation
5. Bigeminal rhythm
6. 3–2 AV Wenckebach
7. Premature complexes
8. First degree AV block
9. Hemiblock

This mode of operation has proven to be useful to the nurse in drawing her attention to changes in rhythm when they occur. The rhythm classification made by the program serves as an important input to the Boolean logic used for decision-making in another program which will be described later.

Other investigators working in the area of computer analysis of the ECG are: Ralph E. Smith, Mayo Clinic, Rochester, Minn. (IBM 1800); Leon Pordy, Mt. Sinai Hospital, New York (IBM 1800); Hubert Pipburger, Veterans Hospital, Washington, D.C. (Control Data 3200); and Ovar Aroedson, University of Umea, Umea, Sweden (Control Data 3200 and IBM 360). To date, no experiences have been reported by these workers relative to rhythm monitoring in the CCU.

HISTORICAL DATA COLLECTION

Attempts are being made to use the computer as a tool for collecting historical data in the CCU. Its abilities to enumerate, store, classify, and analyze the details of the patient's history and clinical course are being put to work in:

1. Accumulating statistics
2. Classifying patients
3. Evaluating therapeutics
4. Correlating biochemical, hemodynamic and historical data

The computer is, therefore, greatly facilitating both the collection of data and the feedback of useful information that will serve not only to standardize and improve care in the units it serves, but also help with practical decision-making related to their operation.

However, data collection by any method is not without problems: how to make the data acquisition process no more time-consuming than is customary using conventional methods; how to develop ways of insuring that the data gets into the machine; and how to make sure that the data which is put in is accurate, are some of the major challenges that face data collectors. There are a few CCU investigators who have overcome some of these obstacles, however, and are already using their statistics and correlations to advantage in decision-making.

At Duke, a 295-question check list is completed on each patient with myocardial in-

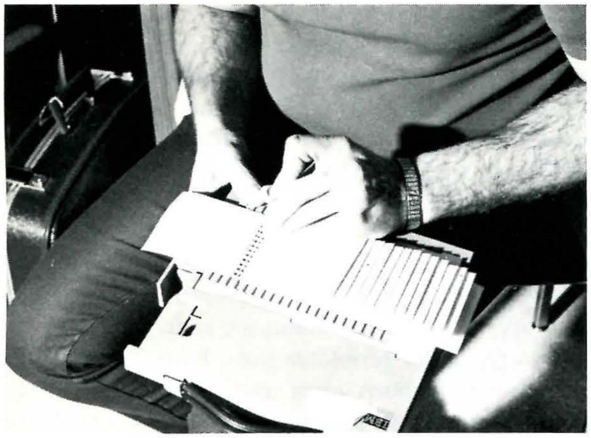

Fig. 3

farction by the house doctor. This check list includes present illness, physical examination, and initial ECG data. The information from this check list is then punched on computer cards which are used not only for inputting the data into the computer record but also for generating a printed history which can be used on the ward. Full histories on 800 patients have already been accumulated, and on 600 of these patients, physiologic, enzyme, mortality, and clinic follow-up data are also in the computer. From this data base, various groups of patients can be formed and the computer can then be asked to either give a display of some particular piece of information, give a 'frequency' of a specific variable, or derive the mean or standard deviation of some measured physiological parameter. For example, by using data obtained at the time of hospitalization and at one year of follow-up, it has been possible to define groups of patients with a high (>50%) and low (<5%) death risk during the follow-up period. The group from Duke has stressed that computer-based techniques for forming homogeneous subgroups of patients and prognostic stratification provide a rational basis for the design of future clinical therapeutic trials. This group also reports that this is one of the most exciting uses they have found for the computer (Wallace, personal communication).

At the LDS Hospital, a complete history which includes a myocardial infarct-oriented present illness, system review, physical examination, initial ECG interpretation, and clinical classification has been developed to get historical data into the computer. This information will be used for comparisons and correlations with hemodynamic and biochemical data. This history is recorded on an IBM data recorder which is a small 4 × 6 box into which a computer card is placed. As the house doctor takes the history and performs the physical examination, he punches holes at locations on the card corresponding to items in the history or physical examination which are present in the patient (Fig. 3). When the history is completed, the patient's hospital number is punched on the card; it is run through the card-reader, which reads the information into the patient's computer record and also generates a printed history which can be used in place of the written or dictated history in the patient's hospital chart. One of the main values of this system, besides its time-saving aspects, is the value it has in educating the house staff as to what questions to ask and how to approach history-taking in a more organized and consistent fashion.

Various groups throughout the country are also interested in collecting data on large numbers of myocardial infarct patients. The objective of these programs is to provide useful statistical information to the smaller hospitals in exchange for the opportunity of using their patient's data to build a large data bank. It is hoped that a method can be developed for classifying patients into uniform populations which would then allow the development of methods for comparing the performance of one unit with another.

An example of such a program is the one being used by the Intermountain Regional Medical Program, to collect admission and discharge data on all patients with myocardial infarcts from 20 hospitals. Their initial objective was the comparison of performance of units throughout the region. Since this could not be done without a method of insuring that patients groupings were uniform, their main effort is now being expended in the development of a good method for classifying patients. Three different methods are being used to get at this information. They are: discriminate analysis, successive screening, and the spacial cluster technique. Some significant problems have been encountered in the collection of this data. These problems have been ones associated with getting reliable data, getting a full set of data on each patient, and finding a way to put a measure of medical intervention into the system (Ford, personal communication).

Rand Corporation, in conjunction with the California Committee on Regional Medical Programs, has also engaged in a Collaborative Coronary Care Unit Data Collection Project (CCRMP). Rand Corporation has supplied the technical experts while the CCRMP cardiologists have supplied project supervision and medical experience. The overall goals of this project are two-fold:

1. To develop a data collection and analysis system to provide local coronary care unit directors and RMP cardiologists with information necessary to assess and improve operating effectiveness of cooperating coronary care units.
2. To study methods of improving coronary care unit efficiency and effectiveness.

This system for data collection is being used in more than 100 California hospitals and hospitals in Missouri, New York, and Vermont; other states are expected to join the study in the near future. Since a wide variety of hospitals have voluntarily joined the study, this data collection system appears to meet a common need of many hospitals to evaluate their CCU relative to the experience of others. This data collection system has already produced several important benefits:

1. It has provided information helpful to the California Committee on Regional Medical Programs in shaping their nurse and physician training programs.
2. The creation of standardized diagnostic nomenclature and statistical data has fostered interaction between hospitals so that common problems can be more readily described and discussed.
3. The system has both stimulated individual research and reduced its cost.
4. The direction of further efforts in statistical evaluation of the CCU has been better defined (Rockwell, 1970).

ADDITIONAL USES OF THE COMPUTER IN THE CORONARY CARE UNIT

A computer program has been written at the Latter-Day Saints Hospital to assist the coronary care nurse or physician with decisions related to the complications of myocardial infarction. It is designed to provide them with early warning and recognition of these complications as well as with therapeutic suggestions. This decision-making program is based upon Boolean algebra and accesses information stored by the computer on 64-word sectors on magnetic disc. Each sector contains a diagnostic or therapeutic message and Boolean statement that makes use of a list of up to 16 variables to make a decision. The program utilizes three basic sources of information:

1. Pressure pulse hemodynamic data from an arterial catheter advanced to the subclavian artery via the radial artery.
2. Arrhythmia data measured automatically from a single lead ECG.
3. Data, such as, CVP, physical examination, X-ray, laboratory, and fluid intake entered manually as comment codes by a technician in the unit.

Each time a measurement is made or a comment entered, the computer searches the patient's record for a combination of factors which would indicate that a complication has arisen. If a combination is found, the computer turns on a red light for the corresponding bed on the computer terminal at the nurse's desk. When the red light button is pressed, a message appears on the scope displaying the decision made. Through another program, the factors upon which this decision was based, can also be obtained and displayed on the scope.

This program, though new and still being modified based on experience with it in the CCU, has already shown its usefulness. An example of the use of this program is furnished by a recent case in the coronary care unit. A 64-year-old male was admitted with a history of two previous infarcts. He was admitted to the unit at 9:00 a.m. on 12-18-70 with severe chest pain and classical findings of an acute anteroseptal infarction. It was noted on his initial ECG that he had left axis deviation, and this, together with other data – physical examination, cardiac rhythms, etc. – was entered into the computer. At 4:00 p.m. of that day he developed a RBBB that was noted by the nurse and entered into the computer. From the program, the combination of RBBB and left axis deviation would bring forth the message 'consider pacing' because this patient has RBBB and left axis deviation, as he did in this case. At 4:30 p.m., just 30 minutes after the above message was displayed, the patient had a cardiac arrest. Luckily, preparations to pace the patient were already being made and a transvenous pacemaker was successfully floated at the bedside.

The ultimate success of this program will depend on two things:

1. The development of simple and sure ways to get clinical information entered into the computer when observations are first made.
2. The willingness of the clinicians who use the programs to provide feed-back as to the performance of the system or the improvements which need to be made.

The computer is also being used in another way in the coronary care unit. It is being used to assist the physician in rapidly retrieving useful hemodynamic and laboratory information on a patient. An attending physician would like to be able to review pertinent data on his patient as quickly as possible when making rounds. At the LDS Hospital, a scope display of these measurements and the time when they were last taken, can be called up on the patient who is being monitored by merely pushing one button, the number of which corresponds to the patient's bed number. These measurements are:

1. Blood pressure (BP)
2. Heart rate (HR)
3. Cardiac output (CO)
4. Resistance (R)
5. Venous pressure (VP)
6. PH
7. P_{CO_2}

8. Po_2
9. K^+
10. Urine output in ml/hr (UO)
11. Cumulative fluid balance (CFB)
12. Temperature (Temp.)

A separate rapid review of hemodynamic information is also available on the scope. The physician can choose one of three ways he wants to review the hemodynamics, i.e., either all at once, one variable at a time, or as a bar graph trend of one variable. He can rapidly review several hours of information and select the time he wants to start his review. These review options are of considerable value in decision-making when a change occurs in a parameter such as systolic arterial pressure. It is easy for the new nurse on duty or the new house-doctor to quickly review back in the record to see if this truly represents a change or whether it is merely a fluctuation which has occurred previously.

Now that clinical laboratories are becoming automated, computerization of measurements for generation of reports and automatic addition of data to the patient's record has not only become possible but highly desirable. At the LDS Hospital, the following measurements are automatically entered on-line into the patient's record from the laboratory and are, therefore, readily available for correlation with other data collected on the MI patient: WBC, RBC, Hgb, Hct, MCHC, MCV, MCH, sodium, potassium, chloride, CO_2, calcium, phosphorus, glucose, BUN, cholesterol, bilirubin, uric acid, SGOT, LDH, alkaline phosphatase, total protein, and albumin.

The continuous monitoring of blood gases and pH could be of great value to the myocardial infarct patient who has sustained significant damage to his left ventricle. At the present time, there are intensive care units throughout the country where the computer is being used with various types of blood gas analyzers to simplify the procedure by making calculations, storing data, or generating reports. The coronary care units have not, at the present, adopted the more aggressive approaches of the intensive care units in monitoring blood gases. In the future, however, with computerized automatic blood withdrawal devices such as those already in use at the Shock Research Unit at Los Angeles County Hospital and at the Primary Children's Hospital in Salt Lake City, and with catheter tip blood gas sensing probes, continuous monitoring of blood gases will be possible.

At the Latter-Day Saints Hospital, blood gases are analyzed by conventional techniques in the laboratory. The computer reads the output directly from the instrument, makes necessary calculations, and logs the information into the patient's record. Once the values are obtained, they are available on the terminal in the unit and a printed report can be obtained. The computer also immediately makes an evaluation on the results or compares them with previous readings. If a value is out of limits, the computer turns on a red light at the terminal in the unit. When the red light button is pushed, a message of instruction will appear. For example, if an arterial Po_2 is below 60, a message will say 'Po_2 56 – notify physician'; and two hours later another red light will come on and give the message, 'Po_2 two hours ago below 60 – should draw another sample'.

It would therefore appear that there are potentially a variety of ways in which the computer could assist the physician and nurse in caring for the coronary care patient. But it also appears that the implementation of its use and the ultimate value it will have in improving care in the coronary care unit will depend primarily upon: (1) the ingenuity of those creating the computer based monitoring system and (2) the degree of communication and understanding established among the bioengineer, computer programmer and clinician.

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